

Partially ionizing the universe by decaying particles

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We show that UV photons produced by decaying particles can partially reionize the universe and explain the large optical depth observed by Wilkinson Microwave Anisotropy Probe. Together with UV fluxes from early formed stars and quasars, it is possible that the universe is fully ionized at $z \lesssim 6$ and partially ionized at $z \gtrsim 6$ as observed by Sloan Digital Sky Survey for large parameter space of the decaying particle. This scenario will be discriminated by future observations, especially by the EE polarization power spectrum of cosmic microwave background radiation.

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I. INTRODUCTION

It was known for many years that the universe, which once became almost neutral after recombination, reionized before $z \sim 5$ by using Gunn-Peterson (GP) test of high redshift quasars. It was not until recently, however, that direct evidences to determine the reionization epoch were found.

First evidence of the reionization epoch was obtained by Sloan Digital Sky Survey (SDSS) [1]. The spectra of quasars observed by SDSS team revealed that there existed neutral hydrogen at the redshift $z \simeq 6$ by GP test, which implies that we have started to see the completion of reionization, although the amount of neutral hydrogen does not have to be very large to explain the observed GP trough.

Recent Wilkinson Microwave Anisotropy Probe (WMAP) observation provided second important evidence of reionization [2]. WMAP found that the optical depth due to the reionization is $\tau_{op} = 0.17 \pm 0.04$, which may correspond to the reionization epoch $z \sim 20$.

Therefore, it is observationally required that the reionization process was very efficient at around $z \sim 20$, but the process did not complete until $z \sim 6$. The conventional view of the reionization process is that the universe is reionized by UV fluxes from early formed stars and quasars. Many calculations have shown that the universe can be reionized at $z \sim 6 - 10$ [3]. Thus, it is possible to explain the full reionization at $z = 6$ observed by SDSS but not what WMAP observed. Recent studies [4, 5] showed that the reionization epoch can be earlier assuming the non-standard initial mass function (IMF) or unrealistically large UV fluxes from galaxies. However, the UV fluxes from stars and quasars increase as time and soon exceed the critical value to fully reionize the universe. Therefore it is expected that the universe achieved the full reionization much earlier than $z \sim 6$ in this scenario. Therefore we need to consider really extreme and perhaps unrealistic assumptions about IMF, escaping UV fraction from galaxies and so on, to have the reionization process with two stages; for example, see [6].

Alternative to along this line, one may also consider

other sources for ionizing hydrogens and heliums. It could be decaying particles, but it has been considered that enduring photon emission from particle decay disables the picture of GP trough confirmed by SDSS. In this article, however, we will show that the optical depth ~ 0.17 can be explained naturally by decaying particles with rather large parameter space of mass and lifetime; in some cases, the lifetime could be longer than the age of the universe. We follow the evolution of hydrogen, helium, and electron temperature including UV sources of quasars, stars, and decaying particles. Here we simply assume the particles decay into two photons with energy half of the particle mass. Notice that Hansen and Haiman [7] tried to explain the optical depth of $\tau_{op} \approx 0.17$ by a particle of mass ~ 200 MeV and the lifetime $\sim 4 \times 10^{15}$ sec, which is $z \approx 20$ reported by WMAP team [2]. They considered the decaying particle as some sterile neutrino which decay into electrons (and positrons) in order to achieve half partially reionized era before $z \sim 6$. Here we will see that photons emitted through particle decay keeps much smaller partially ionization before $z \sim 6$, and explains rather large optical depth.

II. UV SOURCES FOR IONIZATION

We assume that the particle ϕ emits two photons with monochromatic energy of half mass of that particle, i.e., $E_\gamma = m_\phi/2$. The number density of ϕ -particle is written as

$$n_\phi = n_\phi(0)(1+z)^3 e^{-\frac{t}{\tau_\phi}}, \quad (1)$$

where τ_ϕ is the lifetime of ϕ -particle. If $E_\gamma > 13.6$ eV, those photons emitted can ionize hydrogen atoms. Then one can write a source term for the decaying particle as

$$\left(\frac{dn_\gamma}{dt}\right)_{dp} = \frac{n_\phi(t)}{\tau_\phi}. \quad (2)$$

In order to calculate how many photons are emitted, the abundance, mass, and the lifetime of the particle should be fixed. We parameterize them as free parameters by

Ω_ϕ , E_γ , and τ_ϕ . We will see below the allowed region in these parameter space. Notice that we restrict ourselves only for $E_\gamma \leq 10^5$ eV. This is because $E_\gamma \gtrsim$ MeV case involves e^+e^- pair production, and it is too complicated. Moreover, $E_\gamma \gtrsim O(10)$ MeV may destroy light elements such as D, T, ^3He , and ^4He , spoiling successful big bang nucleosynthesis.

Other than decaying particles, we also include usually considered contributions to reionizing photons from quasars and stars. UV photons emitted from early formed stars are indeed responsible for achieving full ionization at $z \sim 6$. UV photons from quasars may keep the ionization fraction unity, but this contribution is very small, and may not be needed for that purpose (Of course, quasars exist and there are contributions from them). We follow the argument of Fukugita and Kawasaki [5, 8] to follow the thermal history from $z > 10^3$ including reionization epoch, calculating the ionization fraction of hydrogen and helium, the photon spectrum, and the electron temperature (see also [9, 10] for treatment of high energy photons from decaying particle).

Some of the difference from Ref. [5, 8] are adoption of decreasing star formation rate for smaller collapsed objects. In Refs.[5, 8] it was assumed that the collapsed objects which satisfy the cooling condition become star-forming galaxies and a constant fraction f of baryons go into stars. In the present paper, we introduce the star-forming efficiency f_{star} which depends on the mass of the objects as

$$f_{star} = \begin{cases} f \left(\frac{M}{3 \times 10^{12} M_\odot} \right)^{0.8} & (M < 3 \times 10^{12} M_\odot), \\ f & (M \geq 3 \times 10^{12} M_\odot), \end{cases} \quad (3)$$

where M is the mass of the collapsed object. With f_{star} the mass function of galaxies obeys the form of an empirical Schechter function at $z = 0$. Since we expect that the UV fluxes from stars reionize the universe at relatively low redshift ($z \simeq 6$), we do not have to take extreme values for model parameters such as the UV escape fraction F_{UV} and f . We take $F_{UV} = 0.04^\dagger$ and $f = 1$ which give the metallicity $Z \approx 0.01$.

In order to estimate the UV contribution from quasars we use the luminosity function in Refs.[12] and [13], from which we obtain the UV emissivity ($1/\text{s}/\text{cm}^3$) at 4400\AA as

$$\left(\frac{dn_\gamma}{dt} \right)_{QSO} = \begin{cases} 5 \times 10^{-23} 10^{-0.47(z-2)} h & (z > 2), \\ 5 \times 10^{-23} h \left(\frac{1+z}{3} \right)^{3.5} & (z \leq 2), \end{cases} \quad (4)$$

where h is the Hubble constant in units of 100km/s/Mpc . We also assume a power law spectrum for quasars,

$$\left(\frac{d^2 n_\gamma}{dt dE_\gamma} \right)_{QSO} \propto \begin{cases} E_\gamma^{-0.7} & (E_\gamma < 10.2 \text{ eV}), \\ E_\gamma^{-1.4} & (E_\gamma \geq 10.2 \text{ eV}). \end{cases} \quad (5)$$

[†] We take $F_{UV} = 0.005 - 0.01$ for longer lifetime than the age of the universe for $E_\gamma = 15$ eV.

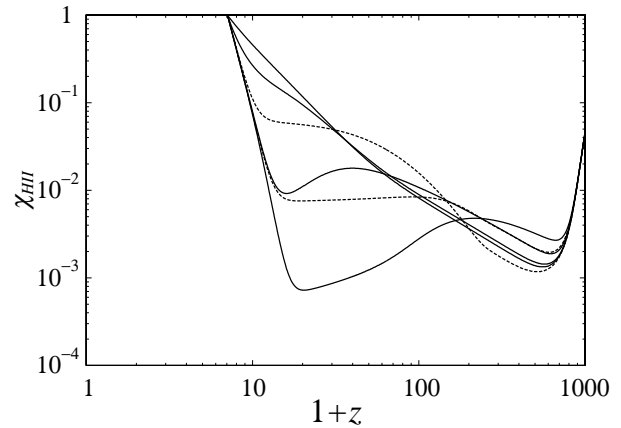


FIG. 1: Ionization histories of hydrogen (HII). We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}$, 10^{15} , 10^{16} , and 10^{18} sec in solid lines from the bottom to the top (at $z \sim 20$), while lower and upper dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively.

We set the cosmological parameters following WMAP-only [2]: $H_0 = 72 \text{ km/s/Mpc}$, $\Omega_m = 0.29$, $\Omega_\Lambda = 1 - \Omega_m$, $\Omega_b = 0.047$, and $\sigma_8 = 0.9$. Apparently, we are dealing with Λ CDM universe, and the decaying particle is assume to be a part of cold dark matter,[‡] but could be hot dark matter with negligible contribution to the total density of the universe.

III. IONIZATION HISTORY

We follow the evolution of the fraction of ionized hydrogen and helium, in addition to electron temperature. Figure 1 shows ionization history of hydrogen for $E_\gamma = 15$ and 10^5 eV for various lifetime τ_ϕ . In each case, the abundance of ϕ -particles is determined in such a way that the optical depth reads $\tau_{op} \simeq 0.17$, which we define by

$$\tau_{op} = \int_0^\infty dz \sigma_T \left(\frac{dt}{dz} \right) [n_{HII} - n_{HII}|_{sr}], \quad (6)$$

where σ_T is the Thomson cross section and $n_{HII}|_{sr}$ is the number density for standard recombination. We subtract this term in order to estimate only the effect of reionization.

In cases for $E_\gamma \lesssim 30$ eV, the lifetime of ϕ -particle is allowed for many orders of magnitude. For longer lifetime than the age of the universe, it is the value of n_ϕ/τ_ϕ that concerns with the amount of photon emission, so ionization histories of these cases are identical to that of $\tau = 10^{18}$ sec shown in Fig.1. Notice that the upper limit

[‡] Particles with very small mass such as $\lesssim 10^5$ eV can be regarded as cold dark matter in such a way that a scalar condensate is coherently oscillating.

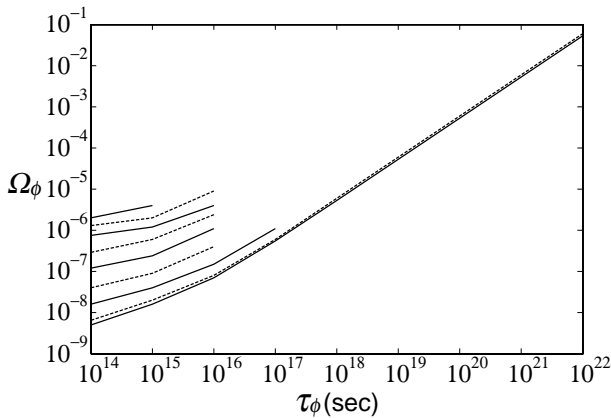


FIG. 2: Allowed region leading to $\tau_{op} \simeq 0.17$. Lines show for $E_\gamma = 15, 30, 10^2, 3 \times 10^2, 10^3, 3 \times 10^3, 10^4, 3 \times 10^4$, and 10^5 eV from the bottom to the top. We exclude those regions where the photon flux exceeds the cosmic X-ray background: typically, $E_\gamma \gtrsim 10^2$ eV and $\tau_\phi \gtrsim 10^{17}$ sec.

of the lifetime is around 4×10^{22} sec, when ϕ -particles is (cold) dark matter, i.e., $\Omega_\phi \simeq \Omega_m$. For shorter lifetime, the abundance should be much less than that contributes to the energy density of the universe. See Fig. 2.

On the other hand, if larger energy of photons are emitted, we have to be careful about cosmic X-ray backgrounds. We adopt the following simple formulas to compare with the calculated photon flux [11]:

$$F_{\gamma,obs} \simeq 8 \left(\frac{E_\gamma}{\text{keV}} \right)^{-0.4} \quad (0.2\text{keV} \lesssim E_\gamma \lesssim 25\text{keV}), \quad (7)$$

$$\simeq 380 \left(\frac{E_\gamma}{\text{keV}} \right)^{-1.6} \quad (25\text{keV} \lesssim E_\gamma \lesssim 350\text{keV}), \quad (8)$$

$$\simeq 2 \left(\frac{E_\gamma}{\text{keV}} \right)^{-0.7} \quad (350\text{keV} \lesssim E_\gamma \lesssim 2\text{MeV}), \quad (9)$$

where $F_{\gamma,obs}$ is measured in units of $(\text{cm}^2 \text{ sr sec})^{-1}$.

We find that long lifetime is not allowed, because the emitted photon flux exceeds the observed diffuse photon background. Thus, the lifetime is rather restricted in the narrow range, and should typically be $\tau_\phi \lesssim 10^{16}$ sec. This constraint is taken into account in Fig. 2, thus the parameter space is restricted for $E_\gamma \gtrsim 10^2$ eV. Hydrogen ionizing histories for $E_\gamma = 10^5$ eV are shown in Fig. 1 as an example. They look very similar to those for $E_\gamma = 15 - 30$ eV. In this case, even $\tau_\phi = 10^{16}$ sec seems to be excluded as is shown in Fig. 2.

Evolutions of ionization fraction of hydrogen look more or less similar in any emitted photon energy for the same lifetime. In order to distinguish them, we need to look at the ionization history of helium. Since larger photon energy can excite helium atoms, one can see the qualitative difference from low energy emitted photons. In Figs. 3 and 4, ionization histories of HeII and HeIII are shown, respectively. We only plotted for $E_\gamma = 15$ and 10^5 eV cases as in Fig. 1.

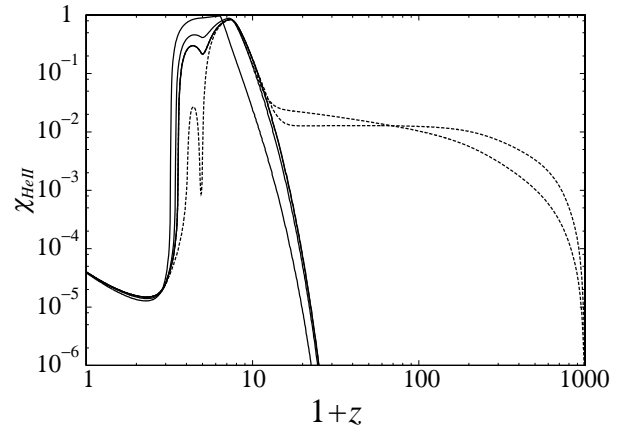


FIG. 3: Ionization histories of helium (HeII). We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}, 10^{15}, 10^{16}$, and 10^{18} sec in solid lines from right to left (near $z \sim 20$), while lower and upper dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively.

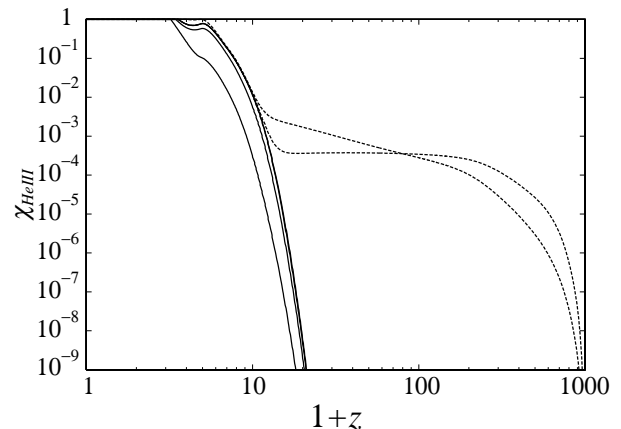


FIG. 4: Ionization histories of helium (HeIII). We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}, 10^{15}, 10^{16}$, and 10^{18} sec in solid lines from right to left (near $z \sim 20$), while lower and upper dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively.

It is trivial to say that rather high ionization fraction begins at high redshift in large E_γ cases. Therefore, although it will be very difficult to observe ionization fraction of helium at $z \gtrsim 20$, it might be one of the tools for (dis)proving the particle decay scenario.

IV. COSMIC MICROWAVE BACKGROUND SPECTRUM

The evolutions of ionization fraction of hydrogen and helium look very different from those instantaneous reionization history usually considered in the literatures, although we obtain the optical depth of ~ 0.17 . So it is interesting to know what we can see, or more precisely, whether we can distinguish them, in the cosmic

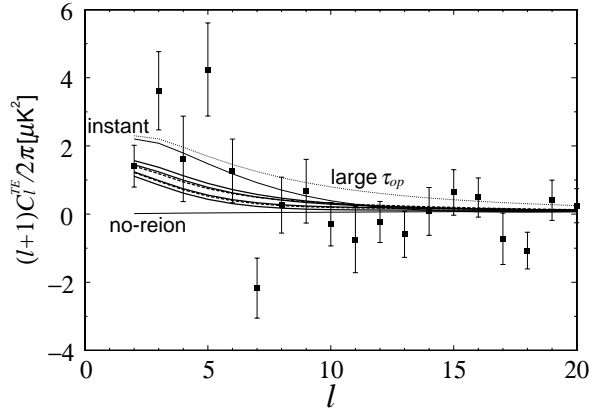


FIG. 5: TE spectrum for various ionization histories. We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}$, 10^{15} , 10^{16} , and 10^{18} sec from the bottom to the top in thick solid lines, while lower and upper thick dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively. We plot no and instantaneous reionization cases in thin solid lines. Higher optical depth case is also shown in dotted line ($E_\gamma = 15$ eV, $\tau_\phi = 10^{16}$ sec, and $\tau_{op} \simeq 0.43$). In addition, WMAP data is placed.

microwave background (CMB) power spectrum. Figure 5 shows the cross correlation spectra between temperature and E-mode polarization. Our models seem to be less power in the small ℓ region than the model with instantaneous reionization. This is because particle decay takes place for longer period, so the power spreads to larger ℓ for fixed value of the optical depth. From the TE spectrum, it is not apparent to distinguish between these models within these error bars. Even difference between the instantaneous reionization and ionization by decaying particles can hardly be seen. Moreover, notice that larger optical depth $\tau_{op} \simeq 0.43$ may account for the observational results of the TE spectrum, too. Of course, it is known that larger optical depth makes the first acoustic peak of the TT spectrum lower. However it can be adjusted by introducing larger spectral index, so-called $\tau_{op} - n$ degeneracy.

Unlike TE spectra, however, EE spectra seem to serve us a much powerful tool for discriminating among different ionization histories,[§] as shown in Fig. 6. Peculiar feature of enduring photon emission from particle decays is larger power around $\ell = (\text{a few}) \times 10$. In addition, there is different feature between long and short lifetime: for long lifetime, the spectrum is rather flat, while there is a dip at $\ell \sim 10$ for short lifetime. Thus, EE spectrum hoped to be seen by Planck satellite or even WMAP should (dis)prove the photons from decaying particles in the near future.

[§] Even in more conventional cases, differences of EE spectra seem to have ability to distinguish among different ionization histories [14, 15].

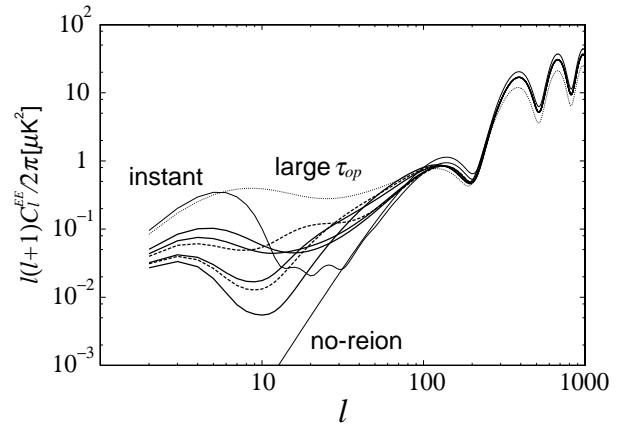


FIG. 6: EE spectrum for various ionization histories. We plot for $E_\gamma = 15$ eV for $\tau_\phi = 10^{14}$, 10^{15} , 10^{16} , and 10^{18} sec from the bottom to the top (at $z \sim 10$) in thick solid lines, while lower and upper thick dashed lines denote for $E_\gamma = 10^5$ eV for $\tau_\phi = 10^{14}$ and 10^{15} sec, respectively. We plot no and instantaneous reionization cases in thin solid lines. Higher optical depth case is also shown in dotted line ($E_\gamma = 15$ eV, $\tau_\phi = 10^{16}$ sec, and $\tau_{op} \simeq 0.43$).

To end this section, we comment on the Compton y_c -parameter. We also follow its evolution, and obtained that the final value is (several) $\times 10^{-7}$ in all the parameters we choose, which is well below the current observational limit [16].

V. CONCLUSION AND DISCUSSION

We have studied comprehensively the ionization history of the universe by photons emitted from decaying particles, together with the effects of stars, quasars, and shown that the decaying particle can explain rather large optical depth observed by WMAP without conflicting other astrophysical and cosmological constraints. One of the amazing fact is that the lifetime of order 10^{15} sec (in other words, $z \sim 20$) is not necessarily required for successful scenario, and larger parameter space is allowed. Since the early star formation ejecting UV photons may be difficult to lead large optical depth without adjusting parameters beyond their natural values, this alternative is at least as good as them.

For $E_\gamma = 10^2 - 10^5$ eV, larger lifetime is prohibited, because the emitted flux exceeds the observed diffuse photon background, and $\tau_\phi \simeq 10^{14} - 10^{16}$ sec is only allowed in these cases. On the other hand, if some bump is observed in the photon spectrum, it could be a great clue for decaying particle scenario.

Longer lifetime is also allowed for $E_\gamma \lesssim 30$ eV. In the limiting case, the decaying particle can be the dark matter, provided that its lifetime is around 4×10^{22} sec. Notice that our situation is different from Ref. [17], in which they investigated for decaying neutrino dark matter and thus using hot dark matter scenario. In this case, ioniza-

tion fraction becomes unity at $z \sim 20-30$, which conflicts with SDSS results. In addition, EURD observation may falsify decaying particle scenario with $E_\gamma \sim 15$ eV, but it needs careful look, since their conclusion will change if the abundance of galactic dark matter near the Sun is one third of their applied value [18].

Observation of CMB spectrum is very powerful. Although instantaneous reionization suggests optical depth $\tau_{op} \sim 0.17$, higher optical depth may be favored for the observed TE spectrum by WMAP if the decaying particle scenario is correct, where slow reionization takes place. It is somewhat difficult to discriminate from each other only by TE spectrum. However, the differences in the EE spectrum is tremendous so we hope that even the lifetime of the decaying particle will be measured by Planck.

Finally, we comment on what can be a candidate for this decaying particle. In the context of no-scale supergravity, scalar particles remain massless at the tree level. They may acquire their masses at one-loop order. Among

them, saxion, the scalar partner of axion in supersymmetric theory, might be the best candidate. If we consider the hadronic axion model, the lifetime is estimated as [19]

$$\tau_s \simeq 10^{15} \left(\frac{F_{PQ}}{10^{15} \text{GeV}} \right)^2 \left(\frac{m_s}{100 \text{eV}} \right)^{-1} \text{sec}, \quad (10)$$

where F_{PQ} is the axion decay constant. It perfectly fits into the allowed region shown in Fig. 2.

Acknowledgments

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